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ANNEALING CONTROL FOR SHEET GLASS

O. N. Shamysheva[1, 2] and R. I. Makarov[1, 3]

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Neutral net models of the annealing of a moving ribbon of sheet glass in a tunnel furnace are developed. The problem of controlling the annealing temperature regime is formulated. Simulation modeling is used to show that the control algorithm is more efficient than manual control of the annealing process. The implementation of a decision-making support system for the production engineer is described.

Key words: sheet glass, annealing, wastes, residual stress, control.

Moving ribbons of float glass are annealed in horizontal furnaces. A glass ribbon is cooled initially in the closed part and then in the open part of the furnace. The closed part of the furnace is divided into the zones *A*, *B*, *C*, *D*, and *E*. Heaters regulating the annealing temperature are placed in the closed annealing zones. Thermocouples are used to monitor temperature. The annealing quality largely depends on the adherence to the annealing regime in the zones of the furnace. Monitored perturbing actions caused by a change of the thickness of the glass being produced, the drawing rate of the ribbon, the temperature of the ribbon going into annealing, the glass density, as well as uncontrolled actions all affect the quality of annealing [1]. A mathematical model has been developed to describe the annealing process (Fig. 1).

The model was constructed using statistical data on the operation of the first polished glass line at the AGC Borskii Stekol'nyi Zavod [AGC Borskii Glass Plant] JSC in the course of one year. The annealing regime was monitored with the thermocouples θ_A, θ_B, θ_C, and θ_D placed in the zones *A*, *B*, *C*, and *D* in the annealing furnace. The perturbing actions were monitored according to the line capacity *Cap*, the thickness δ of the glass produced, and the density D_g of the glass. The quality of annealing was evaluated according to the glass wastes *G* caused by the deviations from the annealing regime and according to the residual stresses σ in the glass. The residual internal stresses of the glass, which are characterized by the difference of the ray paths in birefringence, were determined according to GOST 3519.

Three-layer neural net models with MLP architecture were used to construct a mathematical description of the process. The model of the wastes contains seven neurons in the first layer (at the entrance), 22 neurons in the middle layer, and 1 neuron in the third layer (at the exit). The residual-stress model contains seven neurons, 15 neurons, and one neuron, respectively. The Levenberg–Marquardt method was used to teach the models [2]. The net models developed describe the process annealing process adequately, which made it possible to use these models to develop an algorithm for controlling the annealing process.

The quality of the adjustment of the temperature regime of annealing was evaluated at each control step using a criterion *F* in the form of a penalty function (1):

$$F = \lambda_1 \max\left(\frac{\Delta\theta - \theta_{\text{ad}}}{\theta_{\text{norm}}}, 0\right) + \lambda_2 \frac{G}{G_{\text{norm}}} + \lambda_3\left(\max\left(\frac{\sigma_{\text{low.ad}} - \sigma}{\sigma_{\text{norm}}}, 0\right) + \left|\min\left(0, \frac{\sigma_{\text{up.ad}} - \sigma}{\sigma_{\text{norm}}}\right)\right|\right), \tag{1}$$

where $\lambda_1 - \lambda_3$ are coefficients of the terms in the penalty function; $\Delta\theta = \sqrt{\sum(\theta_s - \theta_f)^2}$ is the change of the temperature in the annealing zones of the furnace at each control step, °C; θ_s is the annealing temperature before the regime is adjusted, °C; θ_f is the annealing temperature after the regime

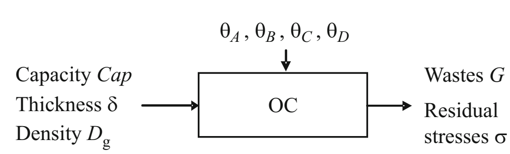

Fig. 1. Model of the object of control (OC).

[1] A. G. and N. G. Stoletov Vladimir State University, Vladimir, Russia.
[2] E-mail: ons33@inbox.ru.
[3] E-mail: makarov.ruslan@gmail.com.

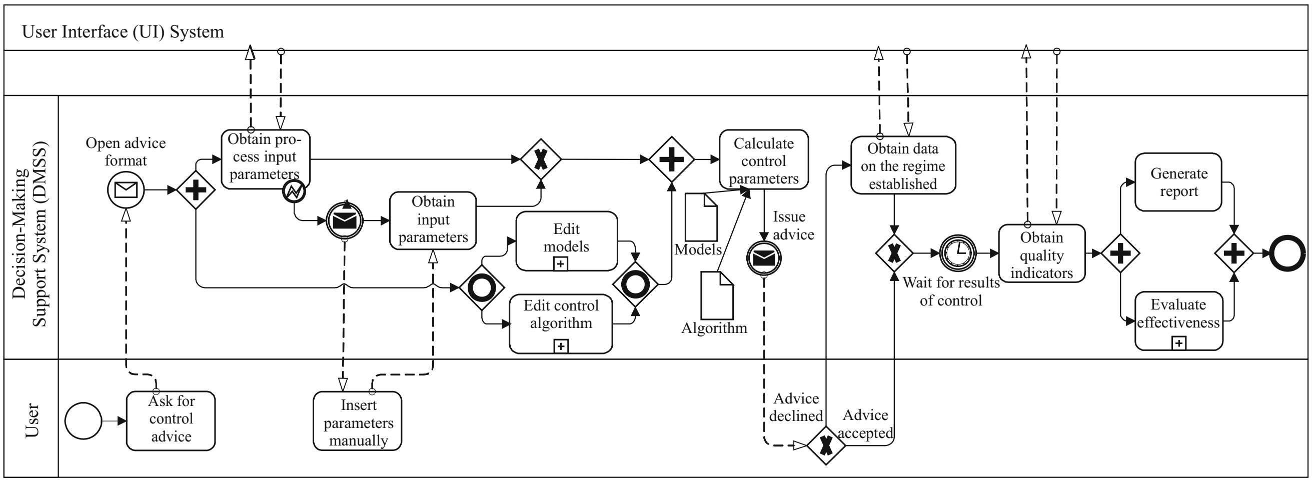

Fig. 2. User interface.

is adjusted, °C; θ_{ad} is the admissible change of the annealing temperature, °C; θ_{norm} is the temperature normalization coefficient, °C; G_{norm} is the normalization coefficient with respect to the annealing wastes, %; $\sigma_{low.ad}$ is the lower admissible value of the residual stresses in the glass, nm/cm, approximated by the relation $\sigma_{low.ad} = (1.1 + 1.7\delta)$; $\sigma_{up.ad}$ is the upper admissible value of the residual stresses in the glass, nm/cm, approximated by the relation $\sigma_{up.ad} = (5.1 + 1.8\delta)$; σ_{norm} is a normalization coefficient with respect to the residual stresses, nm/cm.

The penalty function (1) limits the change of the annealing temperature at a control step, depends linearly on the magnitude of the glass wastes after annealing, and delimits the change of the residual stresses in the glass by lower and upper limits. The numerical values of the coefficients $\lambda_1 - \lambda_3$ were determined by means of a machine experiment: $\lambda_1 = 0$, $\lambda_2 = 0.6$, and $\lambda_3 = 0.4$.

TABLE 1. Comparing the Results of the Simulation Modeling of the Control Algorithm with Manual Control of the Annealing Process

Indicators	Simulation modeling of the control algorithm	Manual control of the annealing process
Average value of the glass wastes, %	0.03	0.59
Standard deviation of the glass wastes, %	0.0001	0.002
Standard deviation of the residual stresses, nm/cm	2.87	3.85
Number of excursions out of the admissible range of variation of the residual stresses	1	18
Number of disruptions of the temperature regime of annealing	2	18

After substituting the values of the coefficients λ_2 and λ_3, the admissible stresses in the glass, and the normalization coefficients into the relation (1) the criterion assumes the form

$$F = 0.6\frac{G}{0.087} + 0.4\left(\max\left(\frac{1.1+1.7\delta-\sigma}{15.0}, 0\right) + \left|\min\left(0, \frac{5.1+1.8\delta-\sigma}{15.0}\right)\right|\right). \tag{2}$$

The problem of controlling the annealing process for the glass was formulated as follows: determine the optimal annealing regime minimizing the value of the penalty function (2) under the conditions (3) imposed on the temperature range in the annealing zones of the furnace:

$$\begin{cases} \theta_{A\min} < \theta_A < \theta_{A\max}; \\ \theta_{B\min} < \theta_B < \theta_{B\max}; \\ \theta_{C\min} < \theta_C < \theta_{C\max}; \\ \theta_{D\min} < \theta_D < \theta_{D\max}, \end{cases} \tag{3}$$

where $\theta_{A\min}$, θ_A, and $\theta_{A\max}$ are the minimum, computed, and maximum temperatures in the zone *A*; $\theta_{B\min}$, θ_B, and $\theta_{B\max}$ are the minimum, computed, and maximum temperatures in the zone *B*; $\theta_{C\min}$, θ_C, and $\theta_{C\max}$ are the minimum, computed, and maximum temperatures in the zone *C*; and, $\theta_{D\min}$, θ_D, and $\theta_{D\max}$ are the minimum, computed, and maximum temperatures in the zone *D*.

The search for the annealing regime was conducted by the method of coordinate descent. To evaluate the efficiency of annealing control, simulation modeling using real data collected over one year from a sheet-glass production line was performed. The results of the simulation modeling of the control algorithm were compared with manual control of the annealing process (see Table 1).

The simulation modeling showed that by controlling the annealing regime using the algorithm developed the glass

wastes can be decreased from 0.59 to 0.03% and the residual stress in the glass stabilized. The evaluations of the control algorithm show that it is desirable to use in the process engineer's decision-making support system (DMSS).

The DMSS has an application window which the engineer can use in the interactive mode. Aside from generating suggestions for adjusting the annealing regime, the system makes it possible to obtain data from the plant's monitoring system PI and formulate answers concerning control, permits editing the models and control algorithms, and delimits user access. The user interface is shown in the diagram represented in the BMN notation – Business Process Modeling Notation (Fig. 2). The system is implemented in the .net 4.0 platform using the C# language in the Visual Studio 2010 development environment. The system accepts the Alglib library, implementing the neural net apparatus.

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